Effect of high pressure homogenization and high power ultrasound on some physical properties of tomato juices at different concentration levels

Francesca Bot[1], Sonia Calligaris*[1], Giovanni Cortella[2], Francesco Nocera[1], Donatella Peressini[1], Monica Anese[1]

[1]Dipartimento di Scienze AgroAlimentari, Ambientali e Animali, Università di Udine, via Sondrio 2/A, 33100 Udine, Italy

[2]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, via delle Scienze 206, Udine 33100, Italy

* Direct correspondence to: Sonia Calligaris

Tel +390432558571

Fax +390432558130

e-mail: Sonia.calligaris@uniud.it

Abstract

The effect of high pressure homogenization (HPH) and ultrasound (US) on some physical properties of tomato juices with different soluble solids content (5.0, 7.5, 10.0 °Brix) was studied. Samples were subjected to HPH up to 150 MPa or US up to 30 min. The energy efficiency associated to the processes was evaluated. Results showed that stress type and product concentration influenced the changes of tomato juice physical properties induced by HPH and US processing. In particular, HPH and US treatments led to similar increases in G' and consistency of 5.0 and 7.5 °Brix juices. These changes were accompanied with redness loss and attributed to cell disruption and consequent increase of inter-particle interactions. Increasing tomato juice concentration to 10.0 °Brix, HPH treatments were more effective than US in changing sample consistency and gel-like properties. The process energy efficiency showed that lower energy was involved in HPH in comparison to US.

Keywords: high pressure homogenization, high power ultrasound, tomato juice concentration, physical properties, energy efficiency

Highlights

- HPH and US caused physical modifications in tomato juice.
- Tomato juice concentration greatly affected process performances.
- HPH caused greater changes in physical properties of 10.0 °Brix tomato juice than US.
- HPH and US were compared in terms of energy efficiency.

1. Introduction

High pressure homogenization (HPH) and high power ultrasound (US) are nowadays proposed as novel techniques to steer desirable structure and functionality of plant-based foods. Changes in the physical properties of biopolymers, such as cellulose, starch, pectin and protein, have been described in fruits and vegetables (e.g. banana, mango, pineapple, peach, tomato, broccoli, carrot) derivatives subjected to HPH and US (Bengtsson and Tornberg, 2011; Calligaris et al., 2012; Kubo et al., 2013; Lopez-Sanchez et al., 2011a; Lopez-Sanchez et al., 2011b; Rojas et al., 2016; Silva et al., 2010). These effects are attributable to the intense mechanical stresses suffering the vegetable matrix during HPH and US processes. In particular, during HPH process, a fluid, which is pumped through a narrow gap valve by means of a pressure intensifier, undergoes intense mechanical forces and elongational stresses at the valve entrance and in the valve gap, while turbulence, cavitation and impacts with the solid surface occur at the gap outlet (Floury et al., 2004a; Floury et al., 2004b). During US treatment, mechanical wave propagation into a fluid may cause cavitation phenomena, which is the spontaneous formation and collapse of bubbles, that leads to the generation of local extreme temperatures and pressures, which in turn produce turbulence and shear stresses (Barbosa-Cánovas and Rodrigues, 2002; Leighton, 1995; Mason, 1998). It has been speculated that the intense stresses delivered by HPH and US lead to cell disruption with leakage of plant constituents, including biopolymers, in the serum. Moreover, processes would modify biopolymer structure by inducing conformational changes as well as reducing polymer size. As a consequence, more polymer chain would be available for bonding, giving rise to novel inter-particle interactions and a different type of network, which is accompanied by a change of the rheological properties (Colle et al., 2010; Seshadri et al. 2003; Thakur et al., 1995). Modification of biopolymers physical properties are reported to highly depend on matrix characteristics and HPH and US intensity, that is pressure level and number of passes applied during HPH, or ultrasonication time (Anese et al., 2013; Augusto et al., 2012; Augusto et al., 2013; Lopez-Sanchez et al., 2011b; Tan and Kerr, 2015; Vercet et al 2002a; Yu et al., 2016). From an industrial

point of view, the choice between HPH and US to steer plant food material physical properties goes through the evaluation of advantages and drawbacks of each technology. Final product characteristics as well as energy and ownership costs would represents the driving criteria. The energy exchanges involved during HPH and US processes are represented by the energy density, which is the amount of energy provided to the fluid per unit volume during the process, as well as the power demand and energy consumption of the equipment (Raso et al., 1999). To our knowledge, very few data are available in the literature about HPH and US energy aspects (Baumann et al., 2005; Bermudez-Aguirre and Barbosa, 2012; Donsì et al., 2013; Mañas et al., 2000; Stang et al., 2001). Cortés-Muñoz et al. (2009) and Calligaris et al. (2016) evaluated the energy density in HPH for an oil/water emulsion by considering the pressure drop. Toma et al. (2011) investigated the energy conversion efficiency in US for organic solvents, and claimed that it is strongly dependent upon the fluid as well as sonication equipment (e.g. its geometry), and the operation mode (e.g. temperature, amplitude of the US field).

Tomato is one of the most worldwide consumed crops. Due to its high versatility, tomato as raw material is widely used to obtain different derivatives, such as juice, puree, pulp, paste, that can be directly consumed or used as ingredients in many food formulations (Gould, 1991). Therefore, it has high relevance for food industry. It has been already demonstrated that both HPH and US might modify tomato physical properties (Anese et al., 2013; Colle et al., 2010; Kubo et al., 2013; Panozzo et al., 2013; Tan and Kerr, 2015). In particular, parameters such as viscosity, consistency, red color and particle size were observed to change in tomato products subjected to HPH and US processes (Anese et al., 2013; Augusto et al., 2012; Augusto et al., 2013; Bayod et al., 2008; Kubo et al., 2013). The application of US in combination with heating (thermosonication) and pressure (manothermosonication) allowed to increase the sole effect of US (Vercet et al., 2002; Wu et al., 2008).

To our knowledge, HPH and US performances in the attempt to deliver functionality of plant-based foods are hardly comparable due to scarce information. Moreover, data on the role of tomato solids concentration in affecting changes in physical properties as induced by HPH or US are fragmentary

(Bayond et al., 2008; Bayod and Tornberg, 2011; Valencia et al., 2003). Therefore, the aim of this study was to investigate the effect of HPH and US on some physical properties of tomato juices with different soluble solids contents. To this purpose, tomato juices with 5.0, 7.5, 10.0 °Brix were subjected to HPH and US for increasing pressure levels or treatment time, respectively, and the changes in their viscoelastic properties, Bostwick consistency, precipitate weight ratio, pectin esterification degree and microstructure were studied. Finally, estimation of the energy density transferred to the juice during processing, as well as measurement of electrical energy consumption of the laboratory devices were performed to compare HPH and US processes from the point of view of energy efficiency.

2. Material and Methods

2.1. Sample preparation

Tomato juice at 5.0, 7.5 and 10.0 °Brix (corresponding to 5.2±0.1, 8.3±0.1 and 10.7±0.1 % dry matter, respectively) was obtained by dilution of commercial tomato paste (21 °Brix) in distilled water. The pH of the juice was 4.5±0.1.

2.2. Treatments

2.2.1. High pressure homogenization

A continuous lab-scale high-pressure homogenizer (Panda Plus 2000, GEA Niro Soavi S.p.a., Parma, Italy) supplied with two Re+ type tungsten carbide homogenization valves, with a flow rate of 2.5 cm^3/s, was used. The first valve was the actual homogenization stage and was set at increasing pressures from 20 to 150 MPa. The second valve was set at the constant value of 5 MPa. Aliquots of tomato juice were introduced into the equipment at 10 ± 1 °C and cooled using an ice bath just after the treatment. The maximum temperature reached by the sample was 45±2 °C.

2.2.2. High power ultrasound

An ultrasonic processor (Hieschler Ultrasonics GmbH, mod. UP400S, Teltow, Germany) with a titanium horn tip diameter of 22 mm was used. The instrument operated at constant frequency and ultrasound amplitude of 24 kHz and 100 μm, respectively. Aliquots of 150 mL of tomato juice were introduced into 250 mL capacity (110 mm height, 60 mm internal diameter) glass vessels. The tip of the sonicator horn was placed in the centre of the solution, with an immersion depth in the fluid of 250 mm. Treatments were carried out for increasing time periods, up to 30 min. During the treatments, the temperature was controlled using a cryostat set at 4 °C to dissipate the heat generated during treatment. Temperature never exceeded 45±2 °C. Following the treatments, the samples were cooled in an ice bath.

2.3. Energy density estimation

The energy density (E_v, MJ/m^3) transferred from the homogenization valve to the sample was determined as described by Stang et al. (2001), according to eq. (1):

$$E_v = \Delta P \qquad (1)$$

where ΔP is the pressure difference operating at the nozzles.

The power density (P_v, kW/m^3) transferred from the ultrasound probe to the sample was determined calorimetrically by recording the temperature (T, K) increase during the treatment, following eq. (2) (Raso et al., 1999).

$$P_v\,(T) = mc_p(\partial T/\partial t)/V \qquad (2)$$

where m is the sample mass (kg), c_p is the sample heat capacity (kJ/kg K), V is the sample volume (m^3), and t (s) is the time frame of treatment considered. The heat capacity was estimated on the basis of sample composition and as a function of the temperature, based on the correlations by Choi and

Okos (1986). Power density is markedly affected by temperature, and its measurement should be performed at adiabatic conditions, which however occur only at the very beginning of the treatment (Raso et al., 1999). In order to achieve at least an estimation of the energy density over the whole treatment while including the effect of temperature, the power density was measured as a function of temperature for a separate test with thermal insulation and without temperature control, up to the maximum temperature of 45 °C.

Later on, the energy density was estimated by integration of the power density as:

$$E_v = \int P_v\,(T)\,dt = \sum (P_v(T)\Delta t) \qquad (3)$$

on the whole treatment time.

2.4. Electrical energy consumption measurement

For both the HPH and US treatments the energy requirement was estimated by measuring the electrical consumption at the mains supply. The high pressure homogenizer was supplied with three-phase 400 V electrical power. Thus a three-phase energy logger was inserted (Kilo Box, Electrex, Reggio Emilia, Italy) to measure the electrical consumption (MJ/m^3) as active power, that is the effective power used by the apparatus, and the power factor, that is the ratio between the "active power" and the "apparent power" related to the power supplied by the net. The power factor is in the range 0-1 and it should be as high as possible for optimal exploitation of the electrical energy supplied. The ultrasonic processor was instead supplied with single-phase 230 V electrical power, and a power meter (PC-300, Lafayette, Taiwan) was connected to measure the electrical power and thus calculate the electrical energy (MJ/m^3) for the whole treatment.

2.5. Analytical determinations

2.5.1. Soluble solids (°Brix)

The soluble solids (°Brix) were measured using a hand Refractometer (Unirefrax, S.A Bertuzzi, Milan, Italy). Measurements were performed at 25 °C. The refractometer prism was cleaned with distilled water before each analysis.

2.5.2. Temperature measurement

The sample temperature was measured just before and immediately after (i.e. before the cooling step) each treatment by a copper-constantan thermocouple probe (Ellab, Hillerød, Denmark) immersed in the tomato juice, connected to a portable data logger (mod. 502A1, Tersid, Milan, Italy).

2.5.3. Colour

Colour analysis was carried out using a tristimulus colorimeter (Chromameter-2 Reflectance, Minolta, Osaka, Japan) equipped with a CR-300 measuring head. The instrument was standardised against a white tile before measurements. Colour was expressed in L*, a* and b* scale parameters and a* and b* were used to compute the hue angle (arctan b*/a*). An increase in hue angle is an index of redness loss.

2.5.4. Rheological properties

Rheological measurements were carried out using a controlled stress rheometer (SR5, Rheometric Scientific, Germany) equipped with serrated parallel plate geometry (40 mm diameter, 2 mm gap). The temperature was maintained constant at 25 °C using a Peltier system. Samples were placed between the plates of the rheometer and left to rest 5 min after loading before testing. This resting time was sufficient for the sample to relax and reach a constant temperature. Dynamic strain sweep tests were carried out at 1 Hz between 0.1% and 100% strain to determine the linear viscoelastic range. Frequency sweep tests were performed from 0.1 to 10 Hz within the linear viscoelastic range. Data obtained were storage modulus (G’), loss modulus (G”) and tan δ (G”/G’). Statistical comparisons were made at 0.1 Hz.

194

195 *2.5.5. Bostwick flow index*

196 Samples were placed into Bostwick consistometer (RG Strumenti srl, Parma, Italy). This empirical
197 test consists in allowing the sample to flow under its own weight along a sloped stainless steel tray
198 for 30 s at room temperature (23 °C). The distance (cm) covered by the sample was recorded and the
199 inverse of the distance (cm^{-1}) was used to express the Bostwick consistency index. An increase of this
200 parameter is associated to high sample consistency.

201

202 *2.5.6. Precipitate weight ratio*

203 Precipitate weight ratio was determined using the method of Colle et al. (2010), with minor
204 modifications. Tomato juice (25 g) was centrifuged (Beckman, Avant J-25 centrifuge, Palo Alto,
205 California, USA) at 45000 *g* for 30 min at 15 °C. The percentage of precipitate weight ratio of the
206 pellet was calculated as:

207

208 $$P = (W_p/W_t) \cdot 100 \qquad (4)$$

209

210 where W_p and W_t are the precipitate and tomato juice weights, respectively.

211

212 2.*5.7. Determination of degree of esterification*

213 The determination of the degree of esterification was carried out using the method of Chou and
214 Kokini (1987). 60 g of tomato juice were centrifuged (Beckman, Avant J-25 centrifuge, Palo Alto,
215 California, USA) at 7500 *g* for 15 min at 20 °C. The supernatant was filtered under vacuum through
216 filter paper (RPE ACS, Carlo Erba, Milano, Italy) and an equal volume of 2-propanol was added to
217 the filtrate to precipitate the isopropanol-insoluble pectins. After 15 min stirring, the suspended solids
218 in the water-isopropanol mixture were centrifuged at 7500 *g* for 15 min at 20 °C and isopropanol was
219 removed by means of vacuum dehydration (Laborota 4001 Efficient, Hedolph Instruments,

220 Schwabach, Germany). The water-soluble pectins were decoloured by acetone:pentane solution (2:1).
221 10 mL 1% decoloured pectin solution were titrated with 0.05 N NaOH (titration A). Afterwards,
222 20 mL 0.5 N NaOH were added to de-esterify the pectin and, after 30 min, 20 mL 0.5 N HCl were
223 added to neutralise the NaOH. This mixture was titrated with 0.1 N NaOH (titration B), using
224 phenolphthalein as indicator. The degree of esterification (DE), expressed as a percentage, was
225 calculated using the following equation:
226
227 $$DE = [B/(A + B) \cdot 100] \quad (5)$$
228
229 *2.5.8. Images*
230 Tomato juice images were captured using a digital camera (Nikon D3, Nikon Corporation, Tokyo,
231 Japan) mounted on an adjustable stand positioned 50 cm above a black cardboard base where the
232 sample was placed. Light was provided by two 250 W frosted photographic floodlights in a position
233 allowing minimum shadow and glare. Images were saved in the jpg file format.
234
235 *2.5.9. Microstructure*
236 Tomato juice microstructure was analysed using an optical microscope (Leica DM 2000, Leica
237 Microsystems, Heerburg, Switzerland) connected to a Leica EC3 digital camera (Leica
238 Microsystems, Heerburg, Switzerland). The images were captured using the 200× objective
239 magnification.
240
241 *2.6. Data analysis*
242 The results are the average of at least two measurements carried out on two replicated experiments
243 ($n \geq 4$). Data are reported as mean value ± standard error. Statistical analysis was performed using R
244 v.2.15.0 (The R foundation for Statistical Computing). Bartlett's test was used to check the

245 homogeneity of variance, one way ANOVA was carried out and Tukey test was used to determine
246 statistically significant differences among means (p<0.05).
247
248 **3. Results and discussion**
249 **3.1 Effect of HPH and US processing on tomato juice physical properties**
250 Fig. 1 shows the macroscopic images of 7.5 °Brix untreated as well as 150 MPa HPH and 30 min US
251 treated tomato juices. Dramatic differences in tomato appearance can be observed between the
252 untreated and treated samples.
253 Tomato juices with 5.0, 7.5 and 10.0 °Brix were subjected to HPH for increasing pressures up to 150
254 MPa or US for increasing time periods up to 30 min, and then undergone to dynamic, small
255 deformation tests to acquire information on structure. Both storage (G') and loss (G'') moduli were
256 frequency dependent and a prevalence of G' over G'' was found, indicating a weak gel-like behaviour
257 of tomato juice (Augusto et al., 2013) (data not shown). The storage modulus and tan δ at a constant
258 frequency (0.1 Hz) were used to compare samples subjected to HPH and US processing (Fig. 2). As
259 a rule, the higher G' and the lower tan δ the more elastic and solid-like the material. G' and tan δ
260 values of HPH and US treated tomato juices were respectively always greater and lower than those
261 of the untreated samples (p<0.05). This suggests a higher number of elastic interactions in processed
262 tomato juices, which resulted in a stronger structure. The extent of changes in viscoelastic properties
263 increased with the increase in juice concentration. In particular, a significant G' increase was found
264 for the 5.0 and 7.5 °Brix tomato juices subjected to HPH up to 50 MPa, while no further increase in
265 storage modulus was observed at higher pressures. By contrast, G' of the 10.0 °Brix tomato juice
266 increased progressively with the increase of pressure, reaching at 150 MPa 4 times higher values than
267 the untreated sample, in agreement with literature (Augusto et al., 2013). Similarly, the storage
268 modulus and tan δ of the 5 min US treated tomato juices, at all concentrations, were respectively
269 higher and lower than those of the untreated samples (p<0.05). No significant changes in the

viscoelastic properties were observed among samples subjected to increasing US times ($p>0.05$). Tomato juice consistency was also evaluated by Bostwick consistometer, which is a widely used tool for quality control at the industrial level. HPH and US induced a significant increase in juice consistency, in agreement with the data relevant to the storage modulus ($p<0.05$) (Fig. 3). Results suggest that both HPH and US were responsible for modifications in the physical properties of tomato samples, which are attributable to cell rupture. As shown in Fig. 4, HPH caused a progressive cell disruption and no intact cells were found upon 150 MPa, while some intact cells were still present in the 30 min US treated sample. As a consequence of cell rupture, the surface area of the suspended particles increased and tomato constituents were released in the medium. In these conditions, novel inter-particle interactions could have been favoured. These events were accompanied by sample colour bleaching (Table 1). Both technologies induced a significant decrease in tomato juice redness at the lesser pressure or time. By increasing the HPH pressure, the colour fading progressively increased, whereas US treatment times higher than 5 min did not cause further colour modifications. No differences in colour bleaching were found among samples with different solids content. ~~It can be inferred that carotenoids were no more protected by cell integrity and underwent to isomerization and oxidation due to cell membrane disruption and their dispersion in the medium (Colle et al., 2010).~~ It can be inferred that HPH and US by disrupting cell membrane caused carotenoids dispersion in the medium, where they underwent to isomerization and oxidation being not more protected by cell integrity (Colle et al., 2010).

To support this hypothesis, the precipitate weight ratio of untreated and treated tomato juices was determined (Table 2). This measure provides an indication of the capacity of the matrix to hold water in the macromolecular network (Colle et al., 2010). The higher the precipitate weight ratio the stronger the network and its water holding capacity. Specifically, increases from 10% to 22% and from 14% to 36% were found for 5.0 and 7.5 °Brix HPH processed tomato juices, respectively. A greater increase up to 46% in the precipitate weight ratio was obtained for the 10.0 °Brix sample subjected to HPH for increasing pressures. Similarly, US treatments caused significant changes of

this indicator compared to the untreated samples in all the tomato juices considered. Treatment times higher than 5 min did not induce further changes of precipitate weight ratio, in agreement with the other indexes previously described for the US processed samples.

Measurement of the pectin esterification degree of the HPH or US processed tomato juices showed that this parameter did not change in comparison with that of the untreated samples, regardless the tomato juice concentration and intensity of process applied (data not shown). This result is in agreement with the literature in the framework of the effect of HPH and US on pectin molecule (Shpigelman et al., 2015; Anese et al., 2013). Thus, the modifications of colour, rheological properties and water holding capacity of tomato juice upon HPH and US treatments can be mainly attributed to physical events than to chemical ones.

Discrepancies in the observed physical properties between samples subjected to HPH and US are likely attributable to differences in modalities of force transmission during processing and thus in mechanical stresses generated by the two technologies. Considering the 5.0 and 7.5 °Brix tomato juices, similar structure modifications were obtained by applying HPH or US, regardless the process intensity. By subjecting to HPH the tomato juice with the highest solids concentration (10.0 °Brix), a dramatic change in the viscoelastic properties was observed. On the contrary, these modifications were not found for the 10.0 °Brix US treated sample. The changes in physical properties of the HPH processed tomato juice suggests that higher particle-particle interactions took place leading to the formation of a stronger network. It can be inferred that the crowding in the homogenization valve increased by increasing the number of suspended material in the sample, thus favouring interactions and, consequently, inducing an increase in consistency as well as gel-like properties. In these conditions the magnitude of mechanical stresses acting on the particles during the flow through the valve could have become much higher, thus increasing the extent of cell disruption. Our findings highlight that stress magnitude in combination with product concentration is crucial for structure development using HPH. Differently, the particle number increase is expected to reduce the efficacy

of ultrasonication, because the high initial product consistency could hinder wave propagation (Earnshaw, 1998).

3.2 Energy density and electrical energy consumption of HPH and US lab equipment

To estimate HPH and US processes efficiency the energy density and electrical energy consumption were evaluated. Table 3 shows the power density measured at ambient temperature at the beginning of the US treatment, as well as the energy density values for both processes. It appears that the energy density values for the US process were higher than those for the HPH treatment, even if the former are possibly underestimated because of their calculation procedure.

Values of the electrical energy consumption for HPH and US devices are summarised in Table 4. As far as energy consumption of HPH is concerned, the electrical energy values were calculated considering that the lab-scale high pressure homogenizer was capable to treat 2.5 cm^3/s of product. An almost linear correlation between pressure and both electrical energy and power factor was found. Moreover, sample concentration did not affect these parameters. This result was also confirmed by treating deionised water in the high pressure homogenizer. Energy consumption of the US treatment was estimated by integrating the measurements of the instantaneous electric power supplied during the whole treatment. According to Table 4, also US energy consumption did not change significantly with sample solids concentration.

These results show that at laboratory scale the high pressure homogenizer presents quite lower energy consumption than the US device, even if the HPH apparatus employed in this case gave rise to significantly low power factors which call for correction in order to comply with the requirements from the energy supplier.

4. Conclusions

Results of this study highlighted the influence of stress type and food solids concentration on the changes in tomato juice physical properties induced by HPH and US processing.

From an industrial feasibility perspective, these results provide information useful to select the most appropriate process to steer physical properties of tomato derivatives. For tomato juices with concentration equal or lower than 7.5 °Brix, the choice between HPH and US should not be performed on the basis of the induced structure modifications because both technologies led to comparable effects. In this context, equipment and total ownership costs would drive the choice. Despite the study was performed on lab-scale equipment, the estimated energy density transferred to the juice during processing and the equipment electrical energy consumption here reported can be used to compare HPH and US processes from the point of view of operating costs, being higher those relevant to the US technology.

On the contrary, for tomato juices with higher concentration (10.0 °Brix), HPH treatments resulted very effective in changing sample consistency and gel-like properties, in an extent that was not achievable by applying the US process. Thus, the criteria for technology selection should be based on a product perspective rather than on process costs.

Acknowledgments

MA and SC conceived the study and carried out the experiments in conjunction with FB and FN. DP carried out the rheological measurements in conjunction with FN. GC carried out energy computations. All authors participated in manuscript revision and discussion, coordinated and critiqued by MA and SC.

Captions for Figures

Fig. 1. Images of 7.5 °Brix untreated (A), 150 MPa HPH (B) and 30 min US (C) treated tomato juices.

Fig. 2. Storage modulus (G') and tan δ at 0.1 Hz of 5.0, 7.5 and 10.0 °Brix tomato juices subjected to high pressure homogenization (HPH) (A, C) and ultrasound (US) (B, D) processes.

Fig. 3. Bostwick consistency of 5.0, 7.5 and 10.0 °Brix tomato juices subjected to high pressure homogenization (HPH) (A) and ultrasound (US) (B) processes.

Fig. 4. Micrographs of 5.0 °Brix untreated (A), and HPH (B: 20 MPa, C: 50 MPa, D: 100 MPa, E:150 MPa) and US (F: 5 min, G: 15 min, H: 30 min) processed tomato juices.

References

Anese, M., Mirolo, G., Beraldo, P., & Lippe, G. (2013). Effect of ultrasound treatments of tomato pulp on microstructure and lycopene *in vitro* bioaccessibility. *Food Chemistry*, 136, 458-463.

Augusto, P.E.D., Ibarz, A., & Cristianini, M. (2012). Effect of high pressure homogenization (HPH) on the rheological properties of tomato juice: Time-dependent and steady-state shear. *Journal of Food Engineering*, 111, 570-579.

Augusto, P. E. D., Ibarz, A., & Cristianini, M. (2013). Effect of high pressure homogenization (HPH) on the rheological properties of tomato juice: Viscoelastic properties and the Cox–Merz rule. *Journal of Food Engineering*, 114, 57-63.

Barbosa-Cánovas, G.V., & Rodriguez J.J. (2002). Update on non-thermal food processing technologies: Pulsed electric field, high hydrostatic pressure, irradiation and ultrasound. *Food Australia*, 54, 513-518.

Baumann, A.R., Martin, S.E., & Feng, H. (2005). Power ultrasound treatment of *Listeria monocytogenes* in apple cider. *Journal of Food Protection, 68*(11), 2333-2340.

Bayod, E., Willers, E. P., & Tornberg, E. (2008). Rheological and structural characterization of tomato paste and its influence on the quality of ketchup. *LWT-Food Science and Technology*, 41, 1289-1300.

Bayod, E., & Tornberg, E. (2011). Microstructure of highly concentrated tomato suspensions on homogenization and subsequent shearing. *Food Research International*, 44, 755-764.

Bengtsson, H., & Tornberg, E.V.A. (2011). Physicochemical characterization of fruit and vegetable fiber suspensions. I: effect of homogenization. *Journal of Texture Studies*, 42, 268-280.

Bermúdez-Aguirre, D., & Barbosa-Cánovas, G.V. (2012). Inactivation of *Saccharomyces cerevisiae* in pineapple, grape and cranberry juices under pulsed and continuous thermo-sonication treatments. *Journal of Food Engineering*, 108, 383-392

Calligaris, S., Foschia, M., Bartolomeoli, I., Maifreni, M., & Manzocco, L. (2012). Study on the applicability of high-pressure homogenization for the production of banana juices. *LWT-Food Science and Technology*, 45, 117-121.

Calligaris, S., Plazzotta, S., Bot, F., Grasselli, S., Malchiodi, A., & Anese, M. (2016). Nanoemulsion preparation by combining high pressure homogenization and high power ultrasound at low energy densities. *Food Research International, 83*, 25-30.

Choi Y., & Okos M.R. (1987). Effects of temperature and composition on the thermal properties of foods. *Food Engineering and Process Applications,* 1, *93-101*.

Chou, D., & Kokini, J.L. (1987). Reological properties and conformation of tomato paste pectins, citrus and apple pectins. *Journal of Food Science*, 52, 1658-1664.

Colle, I., Van Buggenhout, S., Van Loey, A., & Hendrickx, M. (2010). High pressure homogenization followed by thermal processing of tomato pulp: Influence on microstructure and lycopene in vitro bioaccessibility. *Food Research International,* 43, 2193-2200.

Cortés-Muñoz, M., Chevalier-Lucia, D., Dumay, E. (2009). Characteristics of submicron emulsions prepared by ultra-high pressure homogenisation: Effect of chilled or frozen storage. *Food Hydrocolloids*, 23, 640-654.

Donsì, F., Annunziata, M., & Ferrari, G. (2013). Microbial inactivation by high pressure homogenization: Effect of the disruption valve geometry. *Journal of Food Engineering, 115*, 362-370.

Earnshaw, R.G. (1998) Ultrasound: A new opportunity for food preservation, In: M.J.W Povey and T.J., Mason (Eds.), *Ultrasound in Food Processing* (pp.183-192). Blackie Academic and Professional, Glasgow, UK.

Floury, J., Bellettre, J., Legrand, J., & Desrumaux, A. (2004a). Analysis of a new type of high pressure homogeniser. A study of the flow pattern. *Chemical Engineering Science,* 59, 843-853.

Floury, J., Legrand, J., & Desrumaux, A. (2004b). Analysis of a new type of high pressure homogeniser. Part B. study of droplet break-up and recoalescence phenomena. *Chemical Engineering Science,* 59, 1285-1294.

Gould, W.A. (1991). Tomato production, processing and technology (3rd ed.). CTI Publications Inc., Timonium, ML, USA.

Kubo, M.T.K., Augusto, P.E.D., & Cristianini, M. (2013). Effect of high pressure homogenization (HPH) on the physical stability of tomato juice. *Food Research International,* 51, 170-179.

Leighton T.G. (1995). Bubble population phenomena in acoustic cavitation. *Ultrasound Sonochemistry,* 2, S123–S136.

Lopez-Sanchez, P., Nijsse, J., Blonk, H.C.G., Bialek, L., Schumm, S., & Langton, M. (2011a). Effect of mechanical and thermal treatments on the microstructure and rheological properties of carrot, broccoli and tomato dispersions. *Journal of the Science of Food and Agriculture,* 91, 207-217.

Lopez-Sanchez, P., Svelander, C., Bialek, L., Schumm, S., & Langton, M. (2011b). Rheology and microstructure of carrot and tomato emulsions as a result of high-pressure homogenization conditions. *Journal of Food Science,* 76, E130-E140.

Mañas, P., Pagan, R., & Raso, J. (2000). Predicting lethal effect of ultrasonic waves under pressure treatments on *Listeria monocytogenes* ATCC 15313 by power measurements. *Journal of Food Science, 65*(4), 663-667.

446 Mason T.J. (1998). Power ultrasound in food processing: The way forward. In M.J.W. Povey, T.J.
447 Mason (Eds.), *Ultrasound in Food Processing* (pp.105-126). Blackie Academic and
448 Professional, Glasgow, UK.
449 Panozzo, A., Lemmens, L., Van Loey, A., Manzocco, L., Nicoli, M. C., & Hendrickx, M. (2013).
450 Microstructure and bioaccessibility of different carotenoid species as affected by high
451 pressure homogenisation: A case study on differently coloured tomatoes. *Food Chemistry*,
452 141, 4094-4100.
453 Rojas, M.L., Leite, T.S., Cristianini, M., Alvim, I.D., & Augusto, P.E.D. (2016). Peach juice
454 processed by the ultrasound technology: Changes in its microstructure improve its physical
455 properties and stability. *Food Research International,* 82, 22-33.
456 Raso, J., Manas, P., Pagan, R., & Sala, F.J. (1999). Influence of different factors on the output power
457 transferred into medium by ultrasound. *Ultrasonics Sonochemistry,* 5, 157-162
458 Seshadri, R., Weiss, J., Hulbert, G.J., & Mount, J. (2003). Ultrasonic processing influences
459 rheological and optical properties of high-methoxyl pectin dispersions. *Food Hydrocolloids*,
460 17, 191-197.
461 Shpigelman, A., Kyomugasho, C., Christiaens, S., Van Loey, A. M., & Hendrickx, M. E. (2015). The
462 effect of high pressure homogenization on pectin: Importance of pectin source and pH. *Food*
463 *Hydrocolloids*, 43, 189-198.
464 Silva, V.M., Sato, A.C.K., Barbosa, G., Dacanal, G., Ciro-Velásquez, H. J., & Cunha, R.L. (2010).
465 The effect of homogenisation on the stability of pineapple pulp. *International Journal of Food*
466 *Science and Technology*, 45, 2127-2133.
467 Stang, M., Schschmann, H., & Schubert, H. (2001). Emulsification in high-pressure homogenizers.
468 *Engineering in Life Science*, 1, 151-157.
469 Tan, J., & Kerr, W. L. (2015). Rheological properties and microstructure of tomato puree subject to
470 continuous high pressure homogenization. *Journal of Food Engineering,* 166, 45-54.

471 Thakur, B.R., Singh, R.K., & Handa, A.K. (1995). Effect of homogenization pressure on consistency
472 of tomato juice. *Journal of Food Quality*, 18, 389-396.
473 Toma, M., Fukutomi, S. Asakura, Y., Koda, S. (2010). A calorimetric study of energy conversion
474 efficiency of a sonochemical reactor at 500 kHz for organic solvents. *International Journal of*
475 *Food Microbiology*, 137, 116-120.
476 Valencia, C., Sánchez, M. C., Ciruelos, A., Latorre, A., Madiedo, J.M., & Gallegos, C. (2003). Non-
477 linear viscoelasticity modeling of tomato paste products. *Food Research International*, 36,
478 911-919.
479 Vercet, A., Sànchez, C., Burgos, J., Montanes, L., López-Buesa P. (2002). The effects of
480 manothermosonication on tomato pectin enzymes and tomato paste rheological properties.
481 *Journal of Food Engineering*, 53, 273-278.
482 Yu, Z.-Y., Jiang, S.-W., Cao, X.-M., Jiang, S.-T., & Pan, L.-J. (2016). Effect of high pressure
483 homogenization (HPH) on the physical properties of taro (Colocasia esculenta (L). Schott)
484 pulp. *Journal of Food Engineering*, 177, 1-8.
485 Wu, J., Gamage, T.V., Vilkhu, K.S., Simons, L.K., & Mawson. R. (2008). Effect of thermosonication
486 on quality improvement of tomato juice. *Innovative Food Science and Emerging*
487 *Technologies*, 9, 186-195.
488

489

490 **Table 1**. Hue angle (arctan b*/a*) of 5.0, 7.5, 10.0 °Brix tomato juices subjected to high pressure
491 homogenization (HPH) and ultrasound (US) processes. Data relevant to untreated samples are also
492 shown.

493

Total soluble solids content (°Brix)		**HPH**				**US**		
		Pressure (MPa)				Time (min)		
	Untreated	20	50	100	150	5	15	30
5.0	21^{e}	24^{d}	27^{c}	29^{b}	30^{a}	25^{d}	24^{d}	24^{d}
7.5	23^{c}	27^{b}	29^{a}	29^{a}	29^{a}	23^{c}	24^{c}	23^{c}
10.0	22^{d}	23^{c}	24^{b}	26^{a}	26^{a}	23^{dc}	22^{cd}	22^{dc}

494

495 $^{a, b, c, d, e}$: means with different letters in the same row are significantly different ($p<0.05$)

496 Standard error<1

497

Table 2. Precipitate weight ratio (%) of 5.0, 7.5, 10.0 °Brix tomato juice at subjected to high pressure homogenization (HPH) and ultrasound (US) treatments. Data relevant to untreated samples are also shown.

Total soluble solids content (°Brix)		**HPH**				**US**		
		Pressure (MPa)				Time (min)		
	Untreated	20	50	100	150	5	15	30
5.0	10 ± 2^{d}	14 ± 0^{cd}	18 ± 1^{bc}	20 ± 2^{ab}	22 ± 1^{a}	14 ± 0^{bc}	15 ± 0^{bc}	17 ± 1^{bc}
7.5	14 ± 1^{f}	23 ± 1^{cd}	27 ± 1^{bc}	30 ± 2^{b}	36 ± 1^{a}	20 ± 0^{de}	22 ± 1^{ef}	19 ± 1^{de}
10.0	19 ± 0^{e}	29 ± 1^{d}	37 ± 1^{c}	42 ± 3^{ab}	46 ± 2^{a}	23 ± 0^{de}	23 ± 0^{de}	22 ± 0^{de}

$^{a, b, c, d, e,f}$: means with different letters in the same row are significantly different ($p<0.05$)

506

507 **Table 3.** Energy density values generated during HPH and US of 5.0, 7.5 and 10.0 °Brix tomato
508 juices, and power density at ambient temperature relevant to the US treatment.

Total soluble solids content (°Brix)	**HPH**			**US**	
	Energy density (MJ/m^3)			Power density (kW/m^3)	Energy density (MJ/m^3)
	50 MPa	100 MPa	150 MPa		
5.0	50	100	150	533	612
7.5	50	100	150	916	635
10.0	50	100	150	1316	659

509

510

511 **Table 4.** Electrical energy consumption of the HPH and US lab devices, during tomato juice
512 processing.

Total soluble solids content (°Brix)	**HPH**						**US**
	Electrical energy (MJ/m^3)			Power factor (-)			Electrical energy (MJ/m^3)
	50 MPa	100 MPa	150 MPa	50 MPa	100 MPa	150 MPa	
5.0	317	480	644	0.29	0.41	0.51	1369
7.5	310	464	648	0.28	0.40	0.52	1171
10.0	312	462	645	0.28	0.40	0.51	1250

513

514

515

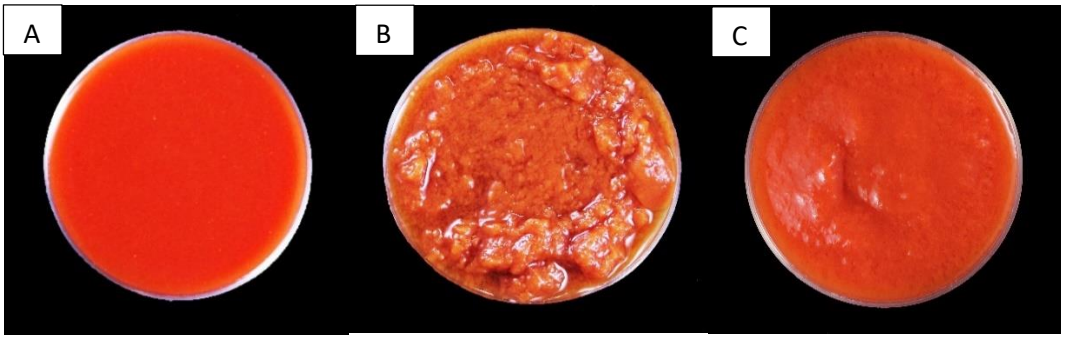


Fig. 1. Images of 7.5 °Brix untreated (A) and 150 MPa HPH (B) and 30 min US (C) treated tomato juices.

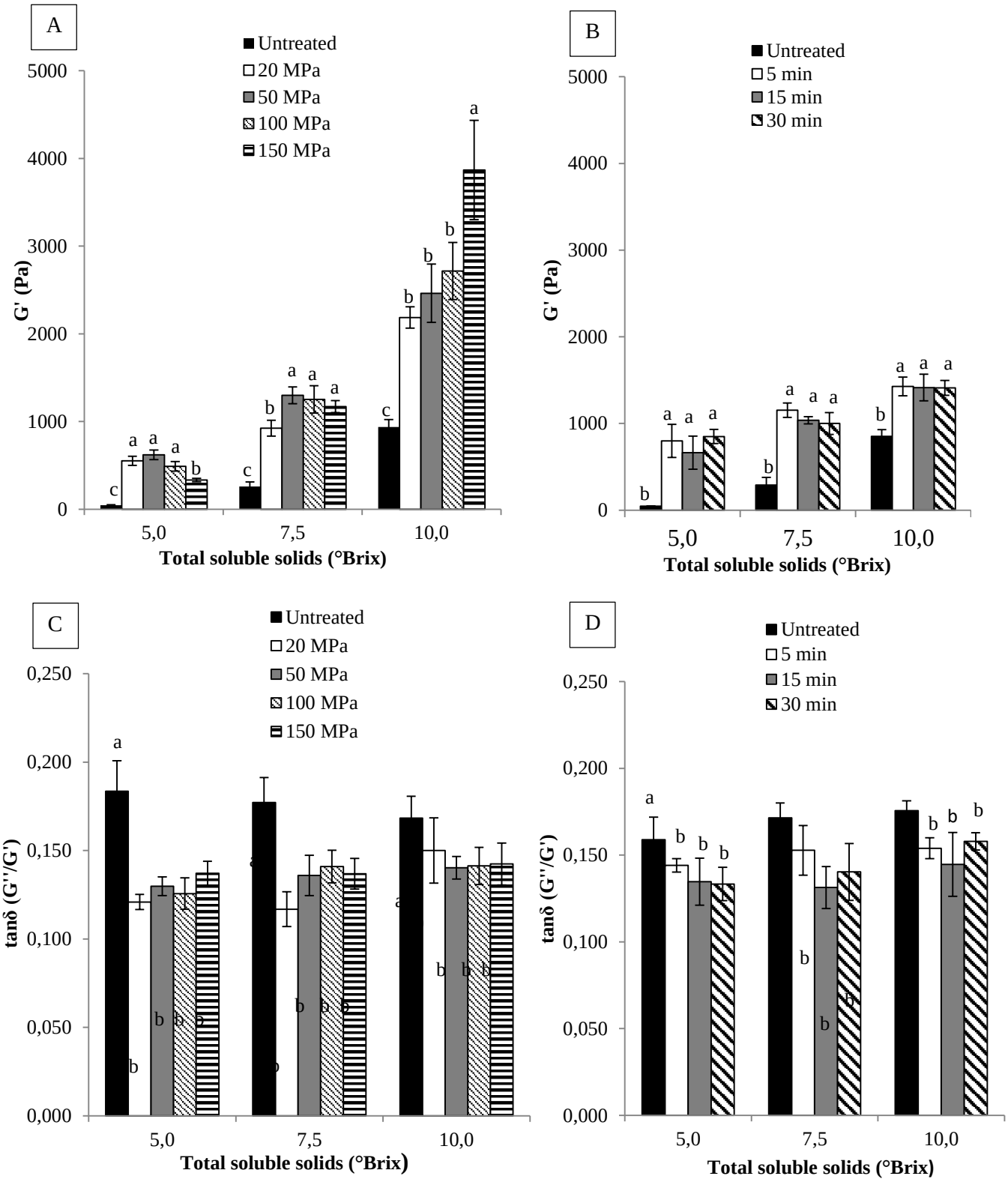
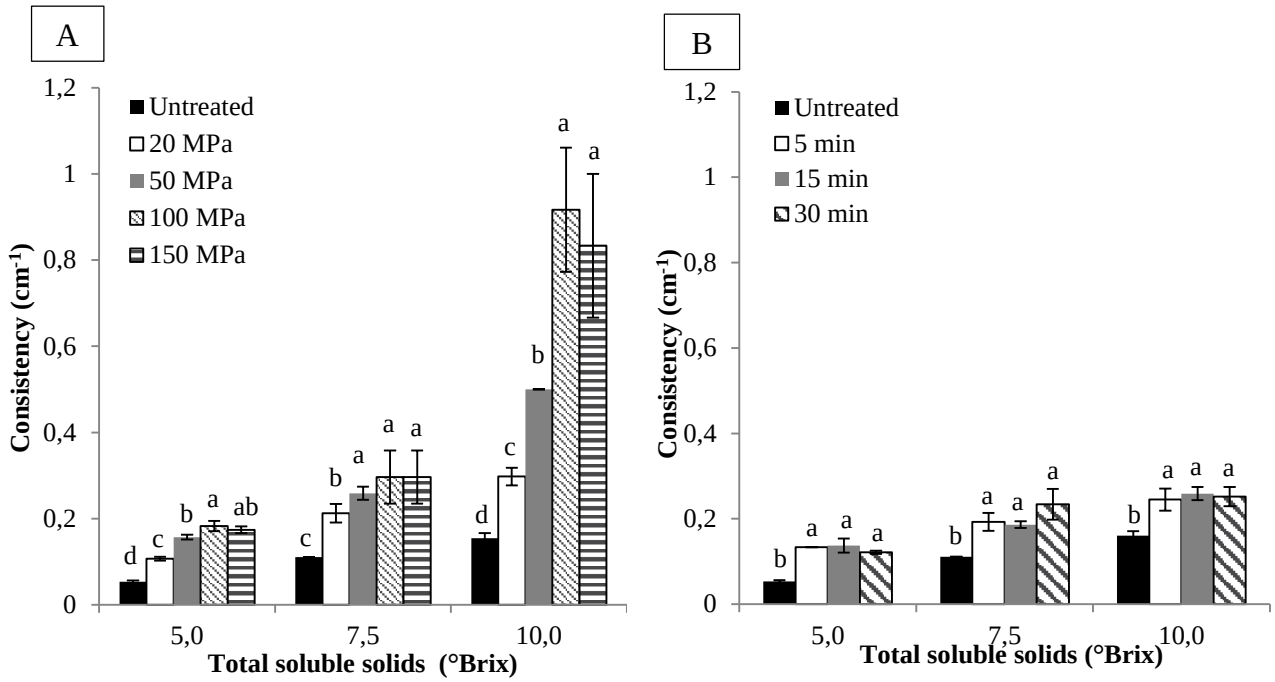


Fig. 2. Storage modulus (G') and tan δ at 0.1 Hz of 5.0, 7.5, 10.0 °Brix tomato juices subjected to high pressure homogenization (HPH) (A, C) and ultrasound (US) (B, D) processes.



537

538 **Fig. 3.** Bostwick consistency of 5.0, 7.5, 10.0 °Brix tomato juices subjected to high pressure
539 homogenization (HPH) (A) and ultrasound (B) processes.

540

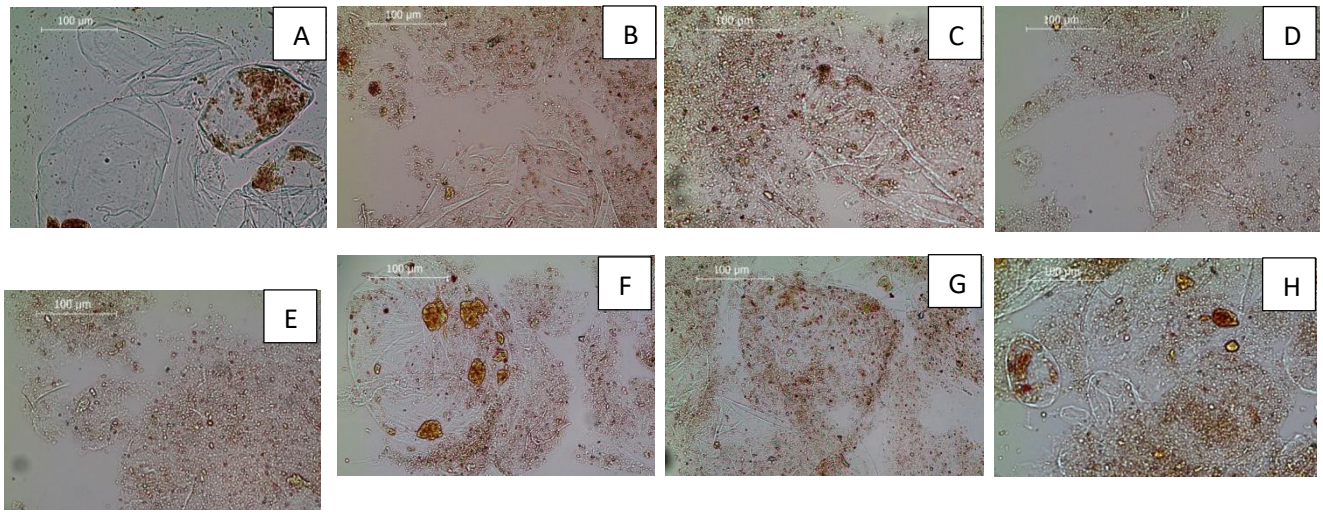


Fig. 4. Micrographs of untreated (A) and 20 MPa (B), 50 MPa (C), 100 MPa (D), 150 MPa (E) HPH processed and 5 min (F), 15 min (G), 30 min (H) US processed 5.0 °Brix tomato juices.